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ADVANCED FLAG-SHAPED SYSTEMS FOR HIGH SEISMIC PERFORMANCE

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SUMMARY

Remarkable improvements have been observed in seismic engineering in the recent past with the development of high-performance seismic resistant systems able to sustain major ground motions with limited levels of structural damage. The developments of dissipation devices, connections and entire seismic resisting systems exhibiting "flag-shape" behaviour, characterized by the combination of self-centering and energy dissipation capacity, significantly reduce the expected level of damage, when compared with traditional monolithic ductile systems. This is achieved by controlling the maximum displacements to target values and limiting (to negligible values) the residual (permanent) deformations occurring after a seismic event. In this paper, the concept of advanced flag-shape systems (AFS) is proposed based on further refinements and improvements of "traditional" flag-shape systems. By appropriately combining the alternative forms of energy dissipation (yielding, friction or viscous damping) in series and/or in parallel together with the main source of re-centering capacity provided by unbonded post-tensioned tendons, mechanical springs or Shape Memory Alloys (SMA) with superelastic behaviour, advanced high-performance seismic resisting systems can be achieved. These are able to counteract the effects of both far field and, more effectively, near field events characterized by a low number of cycles and high velocity pulses. The conceptual behavior and key parameters in the design process of the second generation of flag-shape systems will be first qualitatively discussed using push-pull analyses on SDOF systems. The actual enhanced seismic performance will be subsequently demonstrated by means of non-linear time-history analyses using suites of far field and near-field earthquake excitations.

1. INTRODUCTION

During the past two decades, earthquakes have caused severe damage to many structures leading to millions of dollars lost, highlighting the limitations behind a typical 'ductile design' philosophy which has been primarily focused on collapse prevention. Subsequently, with the introduction of Performance Based Seismic Engineering (PBSE) concepts and preliminary guidelines [SEAOC, 1995] more emphasis has been given to a damage-control design approach. Remarkable improvements have been observed in the last decade of seismic engineering with the development and implementation of high-performance seismic resistant systems able to sustain major ground motions with a limited level of structural damage. The developments of dissipation devices, subassembly connections and entire systems, exhibiting a "flag-shape" behaviour (SMA and PRESSS) [Priestley et al. 1999, Cardone et al. 2004], characterized by the combination of self-centering and dissipation capacity, hence allowing significant reduction of the expected level of damage when compared to traditional monolithic systems. This has been achieved by controlling the maximum displacements to target values and limiting to negligible values the

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residual (permanent) deformations occurring after a seismic event [Christopoulos et al. 2002a; Palermo et al. 2005b; Pampanin 2005]. Concurrently, extensive studies have been carried out to further refine the understanding of the effects of supplementary dampers for seismic protection. Experimental and numerical investigations by Aiken et al. [1993], for example, confirmed the expected efficiency of friction or viscous damping devices in reducing the seismic response. More importantly, attention has been given to the possibility of combining different dissipation mechanisms in order to overcome the inherent limitations of a passive control approach based on a single "tuned" system. Through numerical studies, Makris and Chang [2000] examined the efficiency of various dissipative mechanisms, including viscous (high damping rubber bearings and viscous fluid dampers), rigid-plastic (sliding bearings), elasto-plastic (lead rubber bearings), viscoplastic (sliding bearing and viscous fluid dampers) to protect structures from near field event earthquakes. It has been shown that a combination of a low friction and viscous dampers (in parallel) has a superior performance in reducing the displacement with no significant increase in the base shear. More recently, Kasai and Minato [2005] have been experimentally and numerically investigating the efficiency of a viscoelastoplastic (VEP) dampers based on the combination of viscoelastic and elastoplastic dampers in series.

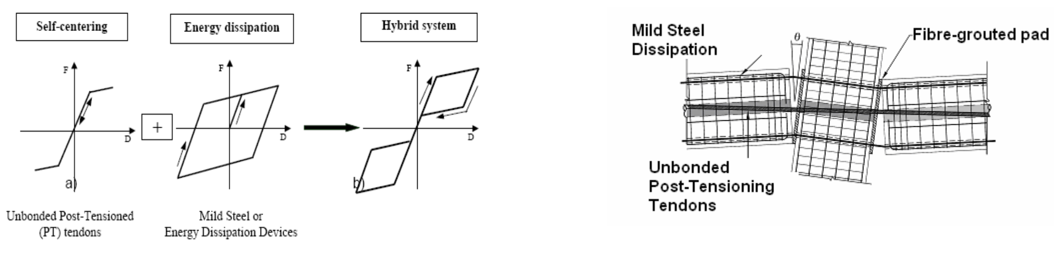
In this contribution, the concept of advanced flag-shape systems (AFS) is proposed based on further refinements and improvements of "traditional" flag-shape systems. By appropriately combining in series and/or in parallel alternative forms of energy dissipation (yielding, friction, viscous or viscoelastic) in addition to the re-centering capacity, provided by unbonded post-tensioned tendons or Shape Memory Alloys (SMAs) with their typical superelastic behaviour, advanced high-performance seismic resisting systems can be achieved. The AFS systems are expected to be able to properly counteract the effects of both far field as well as, more effectively, of near field events characterized by low numbers of cycles and high velocity pulses, which can lead to significantly higher levels of displacement and ductility demands and damage [Alavi and Krawinkler 2001; MacRae et al. 2001]. Traditional hysteretic dampers (displacement-proportional), whose efficiency is typically associated to the development of a full cycle response, should be, in general, considered inherently inadequate to counteract the "fling" effects of a near-field event with velocity-pulse characteristics (as confirmed by the numerical results of Makris and Chang [2000]).

In the first part, the conceptual behavior and key parameters in the design process of alternative configurations of AFS systems will be discussed through cyclic push-pull analyses on single-degree-of-freedom (SDOF) systems. The enhanced seismic performance in terms of displacements demand (both maximum and residual) and peak force demand is also further discussed with a series of inelastic time history analysis using suites of far field and near-field record events.

2. CONCEPTUAL DEVELOPMENT OF ADVANCED FLAG-SHAPE SYSTEMS

2.1 Traditional flag-shape systems

The concept of advanced flag-shape systems (AFS) is proposed based on further refinements and improvements of "traditional" flag-shape seismic resisting systems based on post-tensioning techniques developed for precast concrete buildings [Pampanin, 2005] and subsequently extended to steel frame structures [Christopoulos et al. 2002b], bridge piers [Hewes and Priestley, 1997; Palermo et al.2005a] and more recently LVL (laminated veneer lumber) timber multi-storey buildings [Palermo et al. 2005a]. A traditional flag-shape system combines the re-centering capability from the unbonded post-tensioning cables and the energy dissipating capability from additional energy dissipation hysteretic/yielding devices (either internal or external). Figure 1a shows an idealized flag-shape hysteretic behaviour. The plastic deformation, traditionally carried in plastic hinges of a monolithic ductile connection, is accommodated at the section interface by the opening and closing of the joint under a "controlled rocking" motion. Figure 1b presents examples of application of traditional flag-shaped systems that utilize metallic yielding (internal mild steel) as a form of energy dissipation. **Figure 1: a) Idealized**



hysteretic rule for flag-shape hysteretic rule [Pampanin 2005] b) Example of application of Flag-Shape system for reinforced concrete beam-column joint [NZS3101:2006 Appendix B].

As a result, a properly designed flag-shape system can achieve superior seismic performance when compared with their traditional monolithic counterparts (i.e. elasto-plastic or Takeda hysteresis type of behaviour), guaranteeing a limited maximum displacement and negligible residual (or permanent) displacements. The importance of minimizing residual displacements for an adequate evaluation of seismic performance has been recently highlighted in the literature [MacRae and Kawashima 1997; Pampanin et al. 2002]. For comparison purposes, the standard, bi-linear elastoplastic (EP) model and the traditional flag-shape (FS) SDOF model (as shown in Figure 1(a)) will be included.

2.2 Limits and advantages of alternative types of dissipating mechanisms

As the next rational step of the development of the flag shaped systems, various forms of energy dissipation such as yielding, viscous, viscoelastic, friction in parallel and/or in series are considered as possible combinations with re-centering capacity from unbonded post-tensioning or SMAs. Palermo et al [2005b] have proposed to combine in parallel the concept of unbonded post-tensioning with various forms of energy dissipation as shown in Figure 2. Kurama et. al [2000, 2001] have also proposed the use of supplementary friction or viscous dampers in parallel with unbonded post-tensioned shear walls.

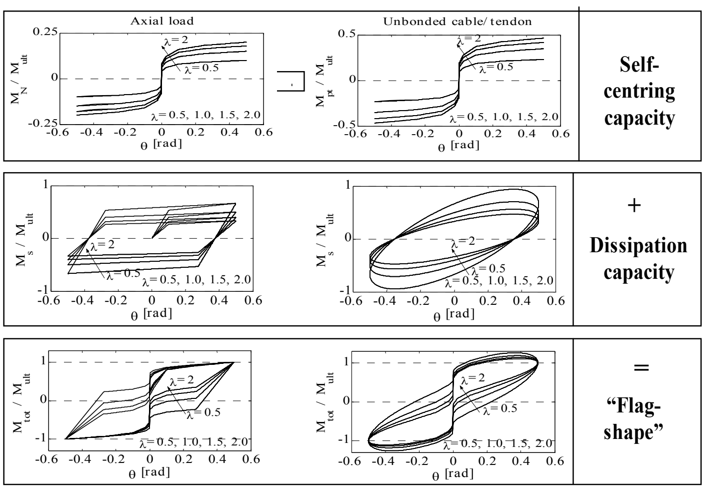


Figure 2: Flag-shape hysteretic behaviour for different dissipation devices: elastoplastic and viscoelastic (adopted – Palermo (2005b))

Each form of energy dissipation has its advantages and limitations in terms of performance. A comprehensive description of different types of energy dissipation is given by Soong and Dargush [1997]. Kasai and Minato [2005] noted that viscoelastic and yielding dampers have different limitations based on the earthquake type and intensity. Kelly [1999] highlighted the issue of high floor acceleration and inter-storey drifts from the use of viscous dampers as part of base isolation systems. Aiken et al [1993] has done extensive experimental tests and provided some notable observations on the behaviour of yielding, friction, viscoelastic and SMA dampers. Table 1 provides a brief summary of advantages and limitations of different types of energy dissipation considered in this study. It is noted that except for yielding dissipation, all other types of dissipation are typically conceived as supplementary (to the bare system) dissipation devices. On the contrary, the concept of advanced flag shaped systems rely on the combination of re-centering elements (i.e. unbonded post-tensioning tendons) and energy dissipative devices as the primary lateral load resisting connection (beam-column joints, column/pier-to-foundation, wall-to-wall or wall-to-foundation).

Table 1: Advantages and limitations of different types of energy dissipation

Type	Large Earthquakes (Far Field)	Large Earthquakes (Near Field)	Small Earthquakes
Yielding	Lower maximum force/acceleration with significantly higher energy dissipation. Possibly large residual deformations.	Relatively low hysteretic energy dissipation because of the few cycles in near field event despite the high peak force. Large peak and residual displacement demand.	Relatively large acceleration and forces under elastic behaviour low energy dissipation at small excitation (without plastic behaviour). Possible low cycles fatigue in long run.

Friction (Supplementary Damping Only)	Friction slip limits the maximum force/acceleration. Large residual deformations.	Relatively low hysteretic energy dissipation because of the few cycles in near field event. Large peak and residual displacement demand.	Perform well for small earthquakes below slipping force with low energy dissipation at small excitation (without plastic behaviour). Possible low cycles fatigue in long run.
Viscous (Supplementary Damping Only)	Possibility of excessive acceleration/force within the superstructure that might cause global failure. Negligible residual deformations.	Effective energy dissipation from high velocity excitation. Excessive acceleration/force might cause failure of structure. Negligible residual deformations.	Effective energy dissipation even at small excitation.
Viscoelastic (Supplementary Damping Only)	Possibility of excessive acceleration/force within the structure that might cause global failure. Temperature dependency.	Effective energy dissipation from high velocity excitation. Excessive acceleration/force might cause failure of structure. Some residual deformation. Temperature dependency.	Effective energy dissipation even at small excitation. Temperature dependency.

2.3 Advanced flag shape system I: combination in parallel of alternative dissipating mechanisms/systems with re-centering contribution

In the first instance, two idealized SDOF models were considered, consisting of the combination in parallel of various energy dissipation devices with the re-centering contribution of unbonded post-tensioning (or other sources or re-centering). Considering an equivalent single degree of freedom (SDOF), the unbonded post-tensioning is modelled using a non-linear elastic spring while yielding dissipation is modelled as bi-linear elastoplastic and viscous dissipation is modelled as a viscous dashpot. Figure 3a and 3b provide the schematic illustrations of two 'parallel' combination systems referred to Non Linear Elastic with Viscous (NLEV), and Advanced Flag Shape System 1 (AFS1).

The NLEV system is conceptually similar to what is shown in Fig. 2. There are however some limitations associated to a pure combination of viscous dampers and unbonded post-tensioning. On one hand, if the excitation velocity is very low (far field earthquakes), viscous dampers would not be effective, resulting in a limited strength and energy dissipation capacity. On the other hand, if the excitation velocity is too high (near field earthquakes), the forces developed in the viscous damper could easily exceed the strength of other parts of the structure, thus leading to undesired level of damage or local failures. Due to these considerations, the Advanced Flag Shape 1 (AFS1) system is herein proposed as a possible viable solution to overcome the aforementioned limitations: by adding yielding (or hysteretic in general) dissipation in parallel to the NLEV system (equivalent to adding a viscous damper in parallel to the traditional flag-shape system) so that a superior seismic behaviour can be expected. At low velocity excitation, the yielding devices can provide the required energy dissipation and strength while at moderate levels of velocity excitation, the inherent advantages of the viscous device, whose dissipation mechanism is proportional to the velocity, can be fully exploited and a reduced level of displacement demand are expected, without significant increase in the internal forces. For excitations with high velocity demand, however, such as those of near-field events, the velocity-dependent nature of the viscous/viscoelastic damper could lead itself to an unexpectedly high increase in the internal force

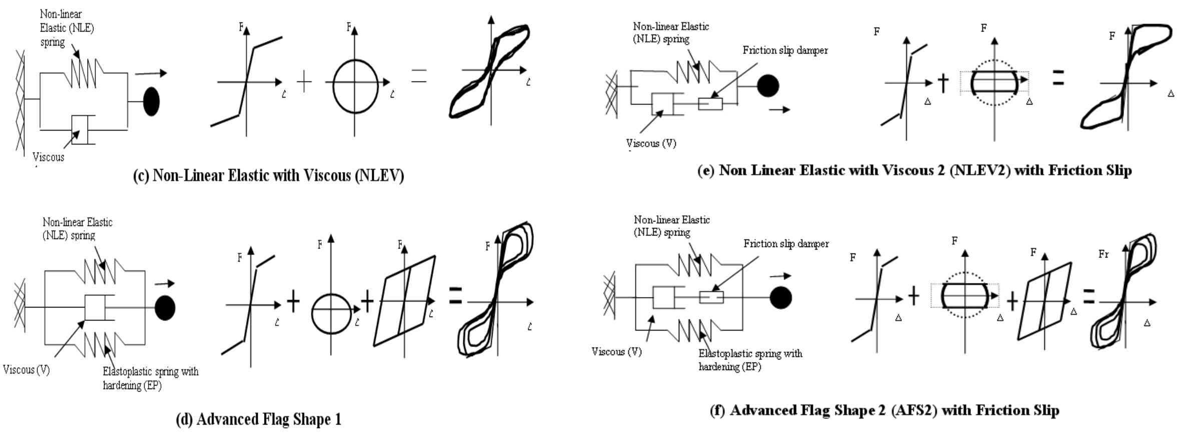


Figure 3: Schematic Illustration of SDOF Models: a) Non-Linear Elastic with Viscous (NLEV) b) Advanced Flag Shape 1 (AFS1) c) NLEV with Friction Slip (NLEVF) d) Advanced Flag Shape 2 (AFS2)

2.4 Advanced flag shape system II:

In order to overcome this limitation, the combination of a hysteretic dissipating element (friction or yielding) in series with a viscoelastic damper can be adopted to limit the force within a velocity-dependent system, as proposed by proposed by Kasai and Minato [2005] and referred to as viscoelastoplastic (VEP) damper.The substitution, into the previously defined flag-shape systems, of a VEP damper instead of a simple Viscous or Viscous elasatic damper would thus have two distinct characteristics:

- Re-centering capability from the unbonded post-tensioning tendons or SMA – hence zero residual displacement is expected.
- Viscous/Viscoelastic in series with friction element allowing energy dissipation to be proportional to velocity instead of displacement – hence effective energy dissipation for low-cycle, high velocity events such as near-field events or small earthquakes (moderate velocity). The friction element would limit the force contribution from the viscous element avoiding overstrength to occur.

The schematic illustrations of the previously defined SDOF models with the subsitution of a VEP system to the Viscous/viscoelastic element is shown in Figure 3c and 3d. The previously defined NLEV system can now be referred to as NLEV with Friction slip (NLEVF). The AFS1 is referred to as Advanced Flag Shape 2 (AFS2).

3. NUMERICAL INVESTIGATIONS WITH PUSH-PULL ANALYSIS

A prototype bridge pier (shown a Fig. 4a) has been designed according to a direct displacement-based design to target displacement of 2% drift for design excitation of a 0.7g, corresponding to peak displacement of 0.87m for 5% damping design spectra. By designing for elastoplastic system of period 1.0sec with displacement ductility of 4, the effective period is 1.6 seconds. This gives a monotonic behavior of the SDOF system illustrated in Fig. 4b.

3.1 Cyclic Push-Pull Analyses

Cyclic Push-Pull analyses were carried out for the six idealized single-degree-of-freedoms (SDOF) models presented in Section 2.1 namely Elasto-Plastic (EP), traditional Flag-Shape (FS), Non-Linear Elastic with Viscous (NLEV), Non Linear Elastic with Viscous in series with Friction or VEP, (NLEVF), Advance Flag-shape 1 (AFS1), and Advanced Flag-shape 2 (AFS2). All the SDOFs were calibrated to have the same monotonic force-displacement envelope of the prototype bridge-pier system under a cyclic sinusoidal push-pull excitation with mean velocity of 15cm/s or frequency of 0.47 Hz. A sinusoidal harmonic excitation is used rather than a 'sawtooth' displacement history as it gives a better representation of force-displacement relationship for a velocity-dependent system. Figure 5 presents the force-displacement cyclic behaviour of the resulting SDOFs models under the cyclic push-pull excitation with a mean velocity of 15cm/s.

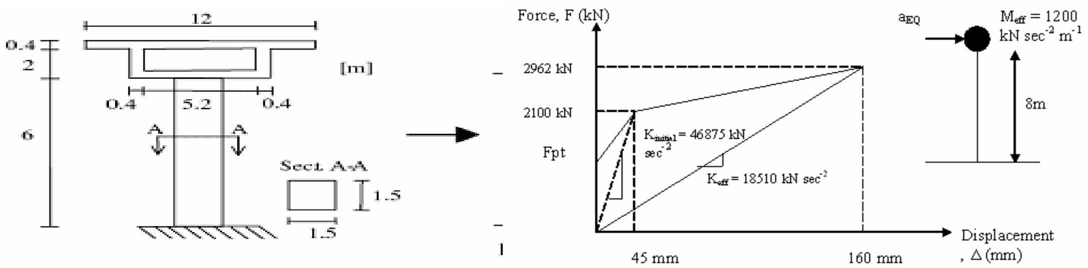


Figure 4: a) Prototype Bridge-Pier b) Equivalent SDOF and its force-displacement monotonic envelope [Palermo et al. 2005b]

The equivalent viscous damping values ξ of the each system evaluated from the hysteresis dissipation contribution at a displacement ductility level of 4 are given in Table 2. As expected, despite having similar monotonic force envelopes, the equivalent viscous damping, ξ varies for each system. The values for EP and FS are consistent with typical values expected for such systems. It is worth noting that the NLEVF systems show lower hysteretic energy dissipation compared to the NLEV due to the strength limit imposed by the friction sliding on the viscous damper (thus limiting its hysteretic contribution). While this could be, in principle, useful under dynamic analyses to limit the force within the system, the reduced level of energy dissipation of the NLEVF has to be accounted for when designing for target displacements. Both the AFS systems have satisfactory high equivelent viscous damping values, ξ , indicative of a possiblly efficient energy dissipation capacity.

Table 2: Equivalent Viscous Damping, ξ of Different Types of Energy Dissipation

SDOF	Equivalent Viscous Damping, ξ
Bi-linear Elastoplastic	53.74
Flag Shape (FS)	13.35
NLEV	26.10
AFS1	24.14
NLEV + Friction	18.83
AFS2	24.14

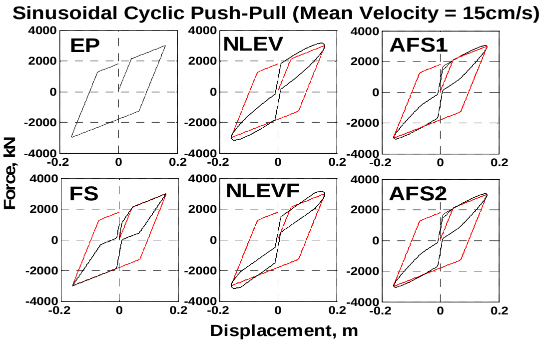


Figure 5: Force displacement plots for SDOF models under sinusoidal cyclic push-pull with mean velocity of 15cm/s – frequency 0.47Hz.

3.2 Controlling Parameters

The design of a traditional flag-shape system is typically carried out by controlling the force or moment ratio, λ_1 of the self-centering contribution (unbonded post-tensioning) and the energy dissipation contribution (yielding elastoplastic or similar behaviour), as given by Equation 1.

$$\lambda_1 = \frac{M_{recentering}}{M_{dissipating}} \approx \frac{F_{NLE}}{F_{YIELDING} + F_{VISCOUS}} \tag{1}$$

For traditional flag-shape systems, a fully self-centering capacity can, in principle, be guaranteed by assuming an appropriate force/moment contribution ratio, λ_1, as $\lambda_1 > 1$, or for safety, $\lambda_1 > 1.15$ [NZS3101:2005, Appendix B]. To reaffirm the same threshold value for λ_1 for the proposed Advanced Flag Shape systems, push-pull analyses are carried out with varying λ_1 values and the results presented in Figure 6. Referring to Figure 6, systems with $\lambda_1 > 1.21$ are observed to have full-re-centering capability. For NLEV systems, the λ_1 threshold appears to be about 0.92. However, it is noted that for systems with only viscous-damping such as NLEV, residual displacement is zero as the viscous damper has zero force resistance when there is no velocity. For the AFS1 and AFS2 systems, the threshold λ_1 appears to be between 0.92-1.21, but the actual re-centering threshold should be lower as both AFS systems have significant viscous-damper contribution (53% of total dissipative force) that has zero residual displacement. The conclusion of these analyses is the existing threshold of $\lambda_1 > 1.15$ for traditional flag-shape is still applicable for the advanced flag shape, but further parametric analysis is necessary to determine a more accurate threshold value as design guideline.

It is proposed here that for advanced flag shape systems which include both viscous and hysteretic components for energy dissipation, an additional force/moment design ratio λ_2–shown in Equation 2 and representing the ratio between the viscous, or velocity-dependent force/moment contribution, M_v, and the total dissipative force/moment, M_{td}, is introduced as part of the design procedure:

$$\lambda_2 = \frac{M_{velocity-dependent-dissipation}}{M_{total-dissipation}} \approx \frac{F_{VISCOUS}}{F_{YIELDING} + F_{VISCOUS}} \tag{2}$$

The λ_2 ratio controls the distribution of velocity-dependent and displacement-dependent dissipation contributions of the system. Therefore, by limiting it to a threshold value, the system can be designed to avoid excessive force/acceleration. The full range (0 to 1) of λ_2 ratio would define all the systems discussed in this paper: NLEV systems would have a λ_2 ratio equal to 1 (100% viscous-damping) while traditional FS systems would have a λ_2 ratio equal to 0 (no viscous contribution). Advanced flag shape systems are between these two extremes. For instance, the calibrated SDOF models of AFS1 and AFS2 would have a λ_2 ratio of 0.56, for the given range of velocity assumed. Figure 7 presents the push-pull hysteretic behaviour of the two AFS systems with varying λ_2 without exceeding friction slip in the AFS2 systems. It is worth noting that the influence of the λ_2 ratio cannot be evident in the force-displacement diagram, the influence of the λ_2 ratio is clearer when considering the ratio between the viscous damping and the total damping as shown in Fig 9b; as a high λ_2 ratio is indicative of high-velocity dependency of the system and a low λ_2 ratio is indicative of low-velocity dependency (more displacement-proportional dissipation).

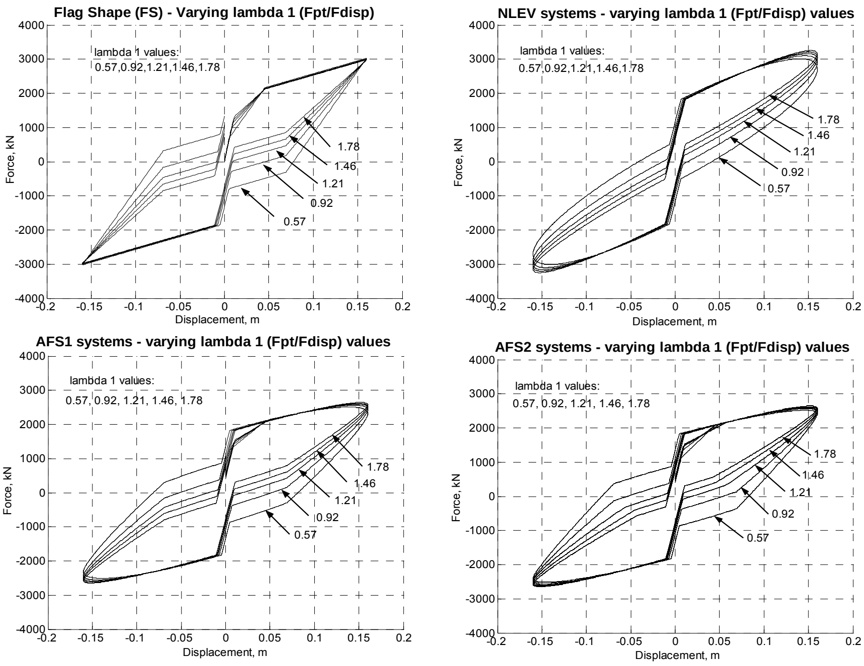


Figure 6: Hysteresis behaviour for the SDOF model – FS, NLEV, AFS1, AFS2 under a cyclic sinusoidal push-pull excitation (velocity = 15m/s/ 0.47Hz) with varying alpha 1 values (0.57-1.78)

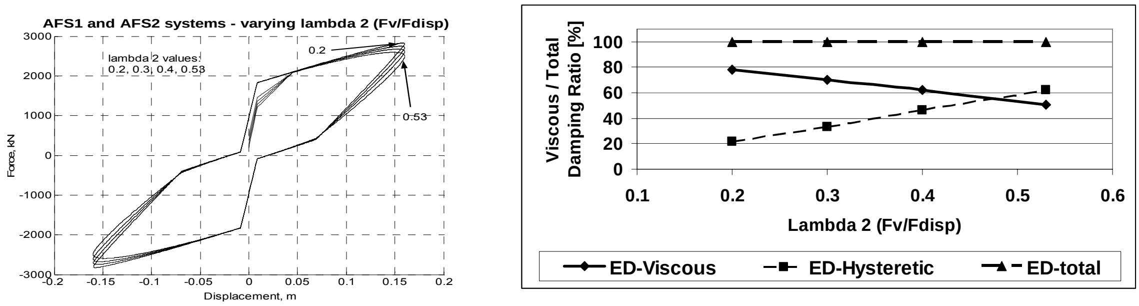


Figure 7: a) Hysteresis behaviour for varying λ_2 for the Advanced Flag Shape systems (AFS1 & AFS2) b) Relationship between Viscous over Total Damping Ratio and parameter λ_2..

3.3 Effect of Excitation Velocity or Frequency

As discussed in Section 2, systems with viscous or viscoelastic dampers might result in excessively high forces generated and transferred to the structural element as the forces in the dampers increase proportionally to the excitation velocity. The proposed combination in-series of viscous damper and friction slipping (VEP concept) can overcome this limitation by setting a slipping force for the combined element. The result of push-pull analyses with varying level of excitation velocities, ranging from 2.5cm/s to 100cm/s, are presented in Figure 8. The advantages of adding a friction slipping element in series with the viscous damper (as in the AFS2 & NLEVF) are evident, as the forces within the systems is limited to a 'designed' level.

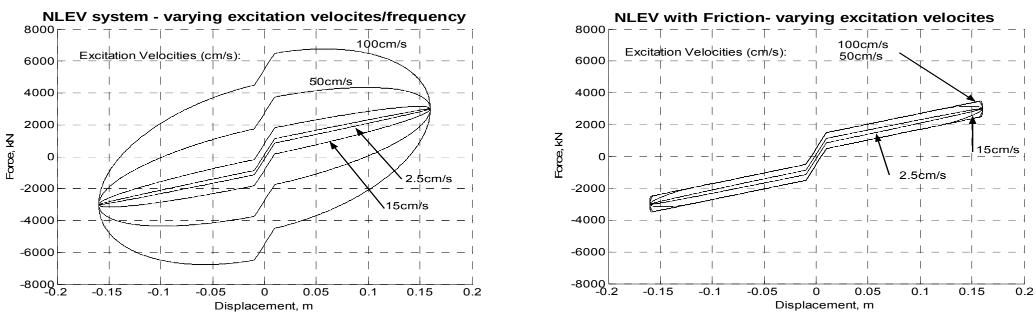


Figure 8: Hysteresis behaviour for NLEV and NLEVF for varying excitation velocities/frequencies.

3.4 Effective Damping (Equivalent Viscous Damping)

The effectiveness of each system in terms of its capability to dissipate energy can be measured by the effective damping or equivalent viscous damping. Figure 9 shows the effects on the equivalent viscous damping of alternative flag shape system evaluated from a sinusoidal push-pull full cycle at displacement level of 4, with average velocities of 15cm/s and 30cm/s when varying λ_1 and assuming the aforementioned values of λ_2 (FS (λ_2=0); NLEV(λ_2=1); AFS1, NLEV2 and AFS2 (λ_2=0.53)). The curves for various systems (hence varying λ_2 values) give us a better picture of the advantage of the AFS systems. For both NLEV and AFS1 systems, both with higher λ_2), substantial equivalent viscous damping can be achieved, especially at higher velocity levels. For the systems with friction slipping elements (AFS2 & NLEVF), the effective damping achieved can be controlled and designed as NLEVF and AFS2 curves are relatively flat for a range of λ_1 values and for both velocity levels.

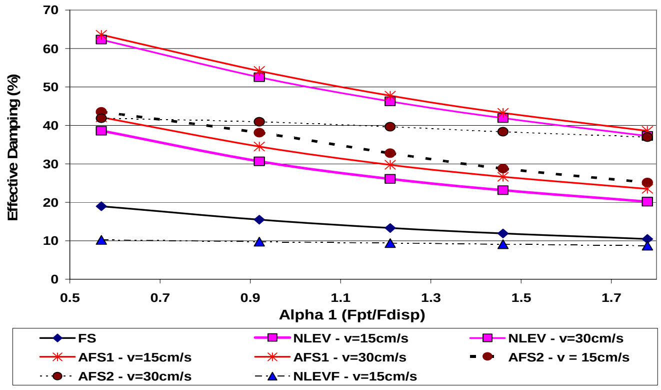


Figure 9: Equivalent viscous damping curves for Varying λ_1 , λ_2 and excitation velocity.

4. NON-LINEAR DYNAMIC TIME HISTORY ANALYSES

4.1 Modelling Assumptions and Selection of Strong Ground Motion Records

An extensive number of non-linear time history analyses were carried out to validate the concept proposed in this paper, and herein only a brief summary of the result is given along with one example for far field and near field responses respectively. The inelastic time history analysis were carried out using the finite-element program RUAUMOKO2D [Carr 2006], A Rayleigh damping model proportional to the tangent stiffness was used with an initial viscous damping assumed to be 5% of the critical damping. Two suites of strong ground motion records were used, representing both far field and also near field events. An ensemble of 20 historical 'far-field' strong ground motion records from California representative of typical earthquakes having a probability of exceedance of 10% in 50 years [Christopoulos et al. 2002a] were adopted in this study. These records were related to soil types C or D (NEHRP categories), with hypocentre depth ranging between 13 and 25km, and were generated by earthquakes of moment magnitude M_w ranging from 6.7 to 7.3. The second suite of earthquakes are three un-scaled near-field earthquake records, selected on their PGV/PGA values and used for quantitative comparison to investigate the effect of the 'near-field'events. As mentioned previously, key characteristics of near-field events are a low number of cycles and high velocity pulses which can yield larger displacement and ductility demands on the structures. [Alavi and Krawinkler 2001; MacRae et al. 2001]. The characteristics of the near field records for the near-field records are presented in Table 3.

Table 3: Near Field Strong Ground Motion Records

Name	Earthquake Event	Year	M_w	Station	$R_{closest}$ (km)	Soil Type (NEHRP)	PGA (g)	PGV (cm/s)	PGV/ PGA ratio
EQ21	Northridge	1994	6.7	Rinaldi Receiving Station	7.1	D	0.84	166.10	0.202
EQ22	Imperial Valley	1979	6.6	El Centro Array #5	1.0	D	0.38	90.50	0.243
EQ23	Hyogo-Ken-Nanbu, Kobe	1995	6.9	Takatori	0.3	C	0.61	127.10	0.212

4.2 Response under Far Field Earthquakes Excitation

Table 4 presents the summary of the responses of the time history analyses under far-field earthquake excitations. In general, all the proposed advanced flag shape systems show a satisfactory behaviour under far field types of earthquake excitation. The full re-centering capacity guarantees negligible residual displacement, while the contribution from the pure viscous damping component gives lower peak displacements when compared to the EP as well as the traditional FS system. Within the family of systems, NLEV and AFS1 show higher mean values of peak force demand, due to the force contribution associated with the viscous damper as a result of the moderately-high excitation velocity, even for far field event. Both NLEVF and AFS2 showed excellent performance in reducing the peak displacement while maintaining a stable peak force.

Table 4: Summary Far Field Earthquakes Inelastic Time History Analysis

Model	Parameters		Peak Force (kN)		Peak Displacement (m)		Residual Displacement (m)	
	λ1 (Fpt/Fdisp)	λ2 (Fv/Fdisp)	Mean	Std	Mean	Std	Mean	Std
Model 1- Elasto-Perfect-Plastic (EPP)	0	0.0	2525	525	0.109	0.049	0.076	0.024
Model 2- PRESSS Flag Shape (FS)	1.2121	0.0	2579	404	0.106	0.045	-0.004	0.010
Model 3 - NLE + VE	1.2121	1.0	3106	735	0.052	0.022	0.000	0.000
Model 4 - Advanced Flag Shape 1 (AFS1)	1.2121	0.56	2665	555	0.064	0.029	0.000	0.001
Model 5 - NLE + V + Friction	1.2121	0.56	2405	496	0.072	0.035	0.000	0.000
Model 6 - Advanced Flag Shape 1 (AFS2)	1.2121	0.56	2427	307	0.079	0.037	0.003	0.001

4.3 Response under Near-Field Earthquakes Excitation

Table 5 presents the statistics summary of the response of the time history analyses under near-field earthquake excitations. Similar trends to the response under far-field types of excitation are, in general, observed in terms of reduced peak displacements as well as negligible residual displacements. However, the adverse effect of excessive force developed by the viscous damper contribution is evident in the near field events where the velocity-pulse, or fling effect, is typically observed. The advantages of implementing a VEP system in parallel with re-centering elements is evident in the higher performance of NLEVF and AFS2 in reducing the peak response while maintaining a stable peak force.

Table 5: Summary Near-Field Earthquakes Non-linear elastic Time History Analysis

Model	Parameters		Peak Force (kN)		Peak Displacement (m)		Residual Displacement (m)	
	λ1 (Fpt/Fdisp)	λ2 (Fv/Fdisp)	Mean	Std	Mean	Std	Mean	Std
Model 1- Elasto-Perfect-Plastic (EPP)	0	0.0	3278	1140	0.202	0.152	-0.018	0.003
Model 2- PRESSS Flag Shape (FS)	1.2121	0.0	3455	1208	0.217	0.157	0.000	0.003
Model 3 - NLE + VE	1.2121	1.0	5101	2882	0.114	0.072	0.000	0.000
Model 4 - Advanced Flag Shape 1 (AFS1)	1.2121	0.56	4059	1965	0.135	0.088	-0.001	0.002
Model 5 - NLE + V + Friction	1.2121	0.56	3936	2046	0.172	0.127	0.000	0.000
Model 6 - Advanced Flag Shape 1 (AFS2)	1.2121	0.56	3288	1255	0.165	0.121	-0.001	0.001

As a confirmation and a clearer example, a comparison of the time-history response of the alternative seismic resisting systems under one far-field event (EQ20 – Yemo Fire Station, Landers 1992) and one near-field event are presented in Figure 13. All the advanced flag shape systems exhibits lower peak displacement and negligible residual displacements. As mentioned previously, the increases in peak force demand due to the viscous element are evident in the NLEV and AFS1 systems, particularly under near-field earthquake excitation. It is also worth noting that the advanced flag shape systems showed significant damping even at low level of displacement because of the viscous (velocity-dependent) damping contribution.

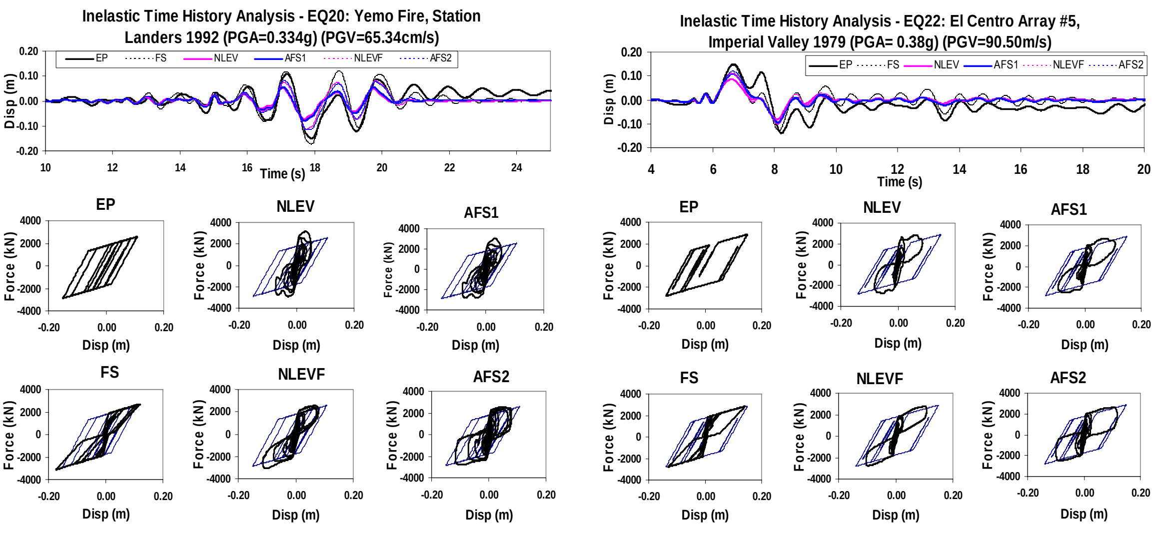


Figure 13: a) Far Field Earthquake Inelastic Time History Plot for EQ20 – Yemo Fire Station, Landers 1992 (M=7.2, PGA =0.334g, PGV=65.34cm/s) b) Near-field Earthquake– EQ22: El Centro #5 Array Station, Imperial Valley 1979 excitation (M=6.6, PGA=0.38g, PGV= 95.50cm/s)

5. CONCLUSIONS

The concept of Advanced Flag Shape (AFS) systems representing where alternative energy dissipation elements (hysteretic, viscous or viscoelastoplastic) are combined in series or in parallel to re-centering contribution has been proposed. This is a further improved version of the existing high-performance seismic resisting system based on flag-shape hysteresis behaviour which is successfully implemented for either new design or retrofit of existing structures. It has been shown via numerical investigations that the AFS systems can reduce peak responses under both far field and near field earthquakes while maintaining fundamental re-centering capability (negligible residual displacements). Peak forces within the system can be controlled by implementing a friction slipping element in series with a viscous damping contribution as shown in AFS2 and NLEVF systems. Two parameters, λ_1 and λ_2, corresponding to the ratio of force/moment contribution of re-centering/dissipative and of viscous dissipating/total dissipating, respectively, have been proposed as part of the design. Experimental and analytical investigations are on-going at the University of Canterbury, to confirm the viability of this second generation of flag-shape systems as well as refine and develop modeling and design procedures.

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